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THE CAUSE OF EARTHQUAKES.

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THE past year has been an exceptional one in the annals of seismology. First San Francisco, then Valparaiso, and now Kingston have been devastated by the shaking of the earth. Naturally, the partial destruction of three populous cities in the Western Hemisphere, within nine months, has aroused an interest in the subject of earthquakes wholly without parallel.

So dramatic has been the recent earthquake history, that a general feeling of alarm has arisen lest one's own home may next be visited. Much speculation has arisen as to the cause of the shaking, and parallels have been attempted between the individual shocks and volcanic eruptions more or less remote. It has come to be widely believed that the earth is passing through a period of unusual instability, and that catastrophe is imminent. Far more space than could be given here would be required even to enumerate the many explanations that have been proposed to account for this supposed unusual condition of the earth. The seen and the unseen, the known and the unknown have been appealed to. Magnetism and radium, sunspots and the moon have all figured in the hypotheses put forward.

Seismologists do not share either the popular apprehension or the wide-spread belief in the earth's unusual instability. Professor John Milne, who, as chairman of the seismological committee of the British Association for the Advancement of Science, has for years kept records of the occurrence and strength of earthquake shocks, has recently stated that there are about sixty world-shaking earth tremors each year. By this is meant such shocks as destroy buildings near the centre of disturbance, and send out waves which are recorded by seismographs the world over.

The unusual feature of the past year has been, not an increase in the number of world-shaking earthquakes, but the occurrence of three of the normal sixty near large centres of population. The other fifty-seven have attracted little or no public attention, either because they did no damage to life and property, or because their effects were felt in regions occupied by people in whom we have little interest.

That within so short a period three large cities have been stricken by the shaking of the earth, must be set down as a coincidence, due to the unfortunate location of three of the great earthquakes of the year; or, shall we not rather say, to the unfortunate location of the cities themselves? Looking back over the records, we find abundant reason to expect each of these cities to be visited by the devastation of the earthquake. On a map of earthquake destruction, each of the cities lies in one of the most heavily shaded parts.

San Francisco is a very young city, but even in its short life, in addition to innumerable minor tremors and slight shocks, there have been a number of quakes of sufficient strength to do damage. The shock of 1898 destroyed a third of a million dollars' worth of property at Mare Island, and damaged many buildings in the city; that of 1868 was of such violence that, had the city then had the area and population of 1906, it would, without much doubt, have been sufficiently destructive to rank as one of the great earthquakes that have occurred in this country. It takes a long time for the strain to accumulate sufficient strength to generate a great earthquake, and San Francisco's history is altogether too brief to warrant the assumption that even the shock of 1906 is the most destructive that that region is capable of.

The coast of Peru and Chile has again and again been visited by destructive earthquakes; and Valparaiso has been devastated more than once. One of the most frightful of modern earthquakes occurred in Jamaica in 1692, when Port Royal, situated on the sand bar at the entrance to Kingston Harbor, was engulfed. Other shocks of violence have also occurred in this island. Thus, in each of these cities, the last earthquake is only one of a series; and the strange feature is not that there have been earthquakes, but that the recurrence of shaking should have happened to affect all three in a single year.

Earthquakes form one of the most inviting phases of geological

study. To their investigation, therefore, a large body of men have devoted a part or all of their time.

Out of all the mass of works relating to earthquakes, it is perhaps not fair to select one for special commendation; yet I believe that most students of seismology will agree with me in the opinion that the one great, epoch-making book on the subject is the recently published "*Les Tremblements de Terre*," by Count de Montessus de Ballore, major of artillery in the French army. Count de Montessus has made it almost a life work to study the distribution of earthquakes, and the ripe results of this study have been published in his recent treatise.

Up to the year 1903, he finds records of 159,784 earthquakes. The plotting of these on a map of the world brings out the striking fact, already known in a general way, that far the greater part of the earth is free from the frequent visitation of earthquakes, and practically immune from violent shocks. Of the nearly one hundred and sixty thousand recorded earthquakes, ninety-four per cent. have occurred in two narrow, well-defined bands forming great circles, and crossing each other at two points. Not all parts of the belts are equally liable to earthquakes, but in them occur almost all the world-shaking earthquakes.

One of these belts, in which has occurred fifty-three per cent. of all recorded shocks, is called by de Montessus the "Mediterranean," or "Alpine-Caucasus-Himalayan," belt. It swings roughly east and west about the earth, and includes the Mediterranean region, Asia Minor, the Caucasus, the Himalayas, the East Indies, Central America, and the West Indies. Where the belt crosses the oceans, little is known about its condition.

The second belt, called by de Montessus the "Circum-Pacific," or "Andes-Japanese-Malayan," belt, almost encircles the Pacific Ocean. Passing along the Andes, it crosses the other belt in the Central-American region, thence extends up the western coast of North America, passes across to Asia along the Aleutian chain, thence down through Kamchatka, the Japanese Islands, and the Philippines, and, crossing the Mediterranean belt in the East Indies, extends on to New Zealand. Forty-one per cent. of all recorded shocks occur in this belt.

All the rest of the world, that is, a surface scores of times greater than the combined area of these two belts, is the seat of

only six per cent. of all recorded shocks. As an indication that this small percentage is not the result of failure to keep records, it may be pointed out that the area where earthquakes are infrequent includes most of the well-settled parts of North and South America, Europe, Asia, Africa and Australia, while a very considerable proportion of the two earthquake zones traverses sparsely settled portions of the earth.

One should not infer from the above figures that regions outside the earthquake belts are actually immune. In the case of the United States there are good reasons for believing that severe shocks are liable to occur in the Great Basin and Rocky Mountain region. East of the Rocky Mountains, shaking of a very minor character has been reported at many places; and in two or three localities there have been really vigorous shocks.

Eastern United States has, indeed, been visited by one earthquake, which, so far as can be judged from the meagre descriptions handed down to us, must be classed as of first rank. This earthquake, commencing late in the year 1811, devastated a part of the Mississippi Valley south of the mouth of the Ohio, being strongest in and about New Madrid. The shaking was repeated at intervals for more than a year, and the first and most violent shock is said to have been felt at points as remote as the West Indies in one direction and New York in the other. The region was sparsely settled and the destruction of property was therefore slight; but the descriptions of the pioneers make it clear that, should such a shock recur in the now well-settled region, the destruction of life and property would be appalling. That the earthquake forces have not completely died out in this section is proved by the fact that other shocks of lesser strength have visited it since 1812.

In the present state of our knowledge, it is probable that no seismologist would venture the prediction of immunity from earthquakes for any part of the globe; but it may be stated that, upon the basis of the records of past earthquakes, the United States east of the Rocky Mountains stands in as little danger from destructive visitations of earth-shaking as any portion of the earth's surface. Only in one locality, or possibly two, does there seem good ground for considering an earthquake of first rank among more than the remotest of possibilities.

The fact that some parts of the earth are peculiarly liable to

be shaken, while other and larger areas are practically free from danger of violent shocks, is, of course, definitely related to the cause of earthquakes. This question of cause divides itself into two parts: first, the immediate explanation of individual shocks, and, secondly, the underlying reason for the conditions by which the immediate cause is able to operate. Upon the first of these questions the work of geologists has thrown much light; as to the other, dealing as it does with the hidden interior of the earth, the answer is not yet found, but an army of workers is engaged in an attempt at its solution.

In general, it may be said that any jar in the earth's crust will cause an earthquake. An explosion of dynamite starts vibrations which pass through the rocks as the waves of an earthquake do. For example, when the passage at Hell Gate was cleared away, some years ago, by a great explosion, the shock was measured on the seismographs at Washington in one direction and Boston in the other. A landslide causes an earthquake; the falling of the roof of a cavern is another cause; and the snapping of rocks under slight strains another.

These are all minor causes for earthquakes, but they account for many of the small tremblings which are felt in a limited area. A much more important cause is volcanic action. The violent eruption of a volcano necessarily jars the earth round about; and even before the eruption shocks are liable to occur; for, as the pent-up lava rises toward the surface, it breaks the rock apart and the molten rock is forced violently into the fissures. This was well illustrated at Vesuvius just before its first great outbreak in historic times. As early as the year 63, A.D., a shock occurred of sufficient violence to injure seriously the buildings in Pompeii, and this damage was not fully repaired when, in 79, the great eruption destroyed and buried that city. As the period of eruption approached, the shocks became of more alarming frequency; and we have the word of Pliny the Younger for it, that the eruption itself was rendered all the more frightful by the rocking of the earth around the Bay of Naples.

Doubtless, if a new volcano should break forth at some point on the earth, its birth would be preceded by repeated earthquake shocks round about the centre of final outbreak; and it is not at all improbable that some of the earthquakes are due to the subterranean movements of lava at points where, as yet,

it has not succeeded in reaching the surface. It is a popular belief that all earthquakes are in some way connected with volcanoes, and when a great and destructive shock occurs, an effort is made to relate it in some way to volcanic activity. Thus, in both the San Francisco and Kingston earthquakes, as in the case of earlier ones, the press announced the outbreak of volcanoes in the neighboring mountains. Such reports were wholly without foundation.

As a matter of fact, while what we may call volcanic earthquakes are common enough, and locally of great violence, they are not usually world-shaking. The reason for this is that the blow which causes the shock strikes only a small area of the crust, and, while the jar may be powerful enough to shake severely the immediate vicinity, it is soon dissipated as its waves spread out from the small centre of disturbance. This being the case, when an earthquake of first violence occurs, and when the seismographs of all the world record it, and especially when it occurs in a non-volcanic region, like San Francisco and Kingston, the inference is at once drawn that it is probably due to some other cause than volcanic action.

This fact, together with the correctness of the inference, was illustrated in the case of the San Francisco earthquake. Immediately after the shock, the newspapers interviewed many geologists of the country who were thought to have knowledge of the subject, and, so far as I saw, to a man they assigned the correct cause for the catastrophe. It was well known that the Coast Ranges are a growing mountain chain; that the rocks there are in a state of strain; that this strain is being steadily increased; that, during the past history of the mountain growth, the strata have been broken and forced to move along the planes of breakage or fault planes; and that, when great masses of rock suddenly slide over one another, even though the movement be but a few feet, the grinding of the strata together must of necessity set the earth trembling. Naturally, therefore, geologists were unanimous in the statement that the San Francisco earthquake was probably due to a movement along one or more fault planes, and the result of normal mountain growth.

Since the earthquake, a State Commission has been carefully studying the facts, and they report that for at least 185 miles there has been a slip, on one side of which the mountains have

been moved bodily in relation to the other side. In this instance, the movement was mainly horizontal, instead of vertical as is normally the case. In places, the shifting amounted to only two or three feet, in others to as much as twenty feet. By it roads were dislocated, fences broken and moved apart, water-pipes separated and long furrows opened in the ground. The movement of a great block of the earth's crust from two to twenty feet, along a plane nearly 200 miles in length, and extending to an unknown depth, but probably thousands of feet, furnishes ample explanation of a shock whose vibrations reached the seismographs in all parts of the earth, and whose area of destruction extended 400 miles in one direction and fifty miles in the other.

There has not yet been a report upon the conditions accompanying the earthquakes of Valparaiso and Kingston; but it is a safe prediction to make that, when the necessary studies have been made, they, too, will be found to be the result of a slipping of the rocks along fault planes. This is the most common cause of violent earthquakes, and, in all probability, of lesser shocks as well. Again and again, when individual earthquakes have been studied, it has been found to be the cause. It has been my fortune to study the conditions associated with one of the most violent of modern earthquakes; and, since the evidence discovered is so clear, and has such direct bearing upon the fault origin of earthquakes, I will briefly outline it. This shock occurred in September, 1899, in and around Yakutat Bay, just southeast of the base of Mount St. Elias. It attracted almost no attention, though the newspapers of the Pacific Coast contained some accounts of it. Yet two of the shocks were so severe that they were recorded on the seismographs at points as remote as Tokio, Cape Town and Rome. In fact, in a recent paper, Dr. Oldham selects this almost unknown earthquake as one of the great modern world shocks. Only a few people were near the centre of shaking,—a party of prospectors camped in Yukutat Bay, and the inhabitants of a small Indian village at its mouth. The accounts of these people make it clear that for two weeks the ground was in a state of almost continuous disturbance, with occasional shocks of terrifying intensity during which it was quite impossible to stand.

Six years later I visited this bay, and to my surprise found the beaches around almost its entire shore elevated above the

present reach of the waves; and mussels, barnacles and other marine animals, dead but still clinging to the cliffs, far above high-water mark. It was evident enough that the coast had been hoisted bodily, and, of course, this meant that the mountains against whose base the beaches rested had been pushed up also. These conditions were studied along 100 miles of coast, and throughout most of its extent the beaches were found to be uplifted from three to ten feet; at one point they were raised fifteen to twenty feet; and along one coast, in a stretch of about three miles, the uplift was from thirty to forty-seven feet. The latter is the greatest uplift of the land so far recorded as having occurred in a single movement.

By plotting the observations on the change of level, it became evident that the movements had occurred, along several fault lines, and that mountain blocks had been differentially uplifted, in one case, as stated, as much as forty-seven feet. Besides the major faults we found several areas of minor uplifts varying from a few inches to three or four feet. Professor John Milne, writing recently on this earthquake, says: "We do not know the magnitude of the masses involved, but, from measurements like those made by Messrs. Tarr and Martin (in Yakutat Bay), we may estimate them as being represented by one or two million cubic miles of rocky material." The sudden readjustment of this amount of rock material is a far more potent cause for violent earth-shaking than the greatest of volcanic explosions.

It is not to be inferred that only great shocks are due to slipping of rocks along fault planes. Striking examples have been selected solely because they present the best and clearest evidence. It is well known that minor slips and adjustments also occur along fault planes, some causing tremors so slight that they would not be known at all were it not for the records of delicate instruments. Such "microseisms" and minor shocks often precede, and almost invariably succeed, great earthquakes. They emanate from the same fault planes, and differ from the great shocks both in the extent of movement along the plane of faulting and in their frequency, for there are hundreds of minor tremors to one great quake. In fact, it is probable that frequent minor movements relieve the accumulating strain, and thus remove the danger of a sudden adjustment of such great extent as to cause a violent shock.

Geological studies of ancient fault planes give us a fair basis for understanding the movements in progress along those modern planes over which rocks are still slipping. In some of these faults the strata on one side have been pushed upward thousands of feet; but the change did not occur all at once. Doubtless, such a fault plane was the source of tens of thousands of shocks, mere tremors when the movement was slight, world-shaking quakes when the strata slipped a few feet along the plane. Near these great faults the rock is usually broken and crushed, showing the intense friction by which the earthquake waves are generated. All mountain regions in which the strata have been folded abound in faults. Where mountain growth is at an end, as in the Appalachians, movements along the planes have practically ceased, and thus a region once an undoubted centre of earthquake activity is now relatively free from such disturbances. But in those mountains which are growing, like the Andes, the Coast Ranges, and the West-Indian chain (in large part submerged), the strains that are causing mountains to rise are still forcing the rocks to move along fault planes.

Exactly what it is that is causing mountains to rise is a question upon which, at present, it is possible to offer only hypothesis. It is known that some mountains, once raised to great height, have not only ceased growing, but have been so long in that state that they have been worn down to low relief. Such is the condition of the mountains of eastern North America from Labrador to Alabama, and of western Europe from Scandinavia to southern England. During the ancient growth of these systems there were volcanoes, and from the evidence of faults, we infer, also, earthquakes. Now the scene is shifted and the same assemblage of growing mountains, volcanoes and earthquakes is present in the two earthquake belts already mentioned. Both volcanic activity and earth-shaking are intimately related to the growth of mountains now as in the past.

The question, therefore, of the ultimate cause of earthquakes, that is of their distribution in belts, is really the question, "What is the cause of mountains?" This is far too great a question for adequate discussion here, and, in fact, it is doubtful if such a discussion would be profitable, since at best, if properly treated, it would lead us only to a series of alternate hypotheses. It must be frankly stated that we do not know what the condition

of the earth's interior really is. Once it was believed to be liquid, later to be solid but highly heated; now we are confronted by the possibility that the heat is a result of radium emanations. The interior of the earth is wholly outside the range of direct observation; and inferences drawn upon its condition must depend upon indirect evidence.

On one point it is my belief that the evidence is clear and conclusive. This is that, whatever its exact condition, the interior upon which the visible rocky crust rests is a yielding mass, even tending to adjust itself to varying loads. It behaves somewhat like a liquid, and tends to maintain a state of isostatic equilibrium. If material is removed from the land, thereby lightening that portion of the crust, and transferred to the ocean bottom, weighing down the crust in that section, there is a down-sinking on the weighted sea floor, a thrust against the land and a rising of the lighter crust near the coast. There are some who believe that this action of isostasy is the main cause for mountain chains; but it seems to me that, while we must admit it as an actually operating cause, we are far from having proof that it is the sole or even the prime reason for mountain growth. A rival hypothesis is that of contraction of the heated globe: and there are other hypotheses also.

That the explanation of mountains has so far baffled investigators, is by no means proof that the problem is insoluble. Never before has it been attacked with such vigor, or by such a body of workers, as at the present day; and among these workers none have made more important contributions to the subject than seismologists. The Japanese have long been engaged in a scientific study of earthquakes; and the Italians have maintained seismological stations at numerous points. Germany, coming into the field later, has, with its characteristic scientific spirit, taken the lead in earthquake investigation on the Continent, with its central station at Strasburg.

The British Association for the Advancement of Science has established a special Seismological Committee, under the direction of Professor John Milne, long a leader in the study of earthquakes in Japan, where he was a professor. Through the influence of this Committee, forty stations have been established in various part of the globe. Very tardily, on the initiative of Professor Hobbs, who at the University of Michigan gives what

is, I believe, the only University course on seismology in America, the American Association for the Advancement of Science at its last meeting established a committee similar to that of the British Association. It will attempt to secure the establishment of seismological stations in the territory and dependencies of the United States.

What can be accomplished by united effort and by numerous widely scattered seismological stations can be inferred from the results already gained, although the movement is only just begun. The immediate cause of earth tremors is understood. The rate of travel of earthquake waves through the earth is now known; and, as a result of their study, far better basis for inference concerning the condition of the earth's interior is now at hand than before these observations began. The actual distribution and the relative intensity of earthquakes are now, for the first time, being recorded over a large part of the earth. The location of earthquakes not reported in the newspapers is made possible by seismographic records; for the time of arrival of the waves and the rate at which they travel, being known, the site of the shock can be closely determined. These are but a few of the scientific results of modern earthquake study, and seismologists are hopeful that by the continuation and broadening of this investigation it may be possible to unravel some of the basal secrets of earth condition and behavior.

If the outcome of these studies were to be wholly of a scientific character, their prosecution might not be of much interest to the general public. But from studies in pure science much of practical value has come forth; in fact, our modern civilization rests primarily upon the foundation of scientific investigation, often carried on wholly without thought of the economic outcome. No one can foretell when or where the most abstruse investigation will touch upon our every-day life.

Earthquakes affect life and property so vitally that one would naturally expect results of economic importance to come out of thorough scientific investigation of the subject. Indeed, some results of importance have already been achieved, and I believe one is warranted in predicting others. It is already known that certain belts are liable to earthquake visitation of destructive character and the limits of these belts are, thanks to de Montessus, fairly well defined. It is further known that certain parts of

these belts are more liable to devastation than others, and some of the more clearly defined earthquake centres are recognized and their limits mapped. With the more careful and thorough studies of the present day, it will not be long before far more will have been accomplished in this direction.

The city of San Salvador, capital of the country of that name, was so frequently devastated by earthquakes that the old site was abandoned; the new one, however, has proved to be but little better. It is by no means improbable that it would be the part of both wisdom and economy to move the sites of other cities in the earthquake belt. A thorough knowledge of the earthquake history of a country would give basis for a proper judgment on this point, and for the selection of a safer new site.

Seismology has lessons to teach in the building of the Isthmian Canal, and it is a grave question whether these lessons have received the attention they deserve. The Nicaragua route lies in a part of the Circum-Pacific belt in which severe shocks are certain to occur, and for this reason it is well that the route selected was further south. The Panama region has not been nearly so subject to earth-shaking as the northern part of South America to the south and the Central-American states to the north. Nevertheless, earthquakes of considerable violence are not unknown even there, and it is by no means certain that equal or greater shocks will not recur. The bearing of this possibility on the question of a lock-canal is evident. A severe earthquake near the Gatun Dam, as now proposed, would cause untold damage and delay. It would show little knowledge of the subject to conclude that, because there has not been a destructive earthquake in the canal zone for several years, or even for a half-century, the danger is absent. There was an interval of 215 years between the earth movements which destroyed Port Royal and Kingston on the same harbor.

When it becomes necessary to build cities in or near earthquake centres, the lessons learned by seismologists are capable of being put to very practical use. It is well known, for example, that structures on loose earth and made land suffer most severely. At Port Royal that part of the city which was built on that sort of foundation slid bodily into the sea, while the buildings on rock were merely injured. The greatest destruction by the San Francisco earthquake was in the districts of made land and loose sand;

and the meagre reports from Kingston indicate that the same phenomenon was repeated there. The reason for this is evident. The violent shaking loosens and moves the earth beneath the foundations, so that, the support being partly destroyed, the building readily collapses under the shaking to which, at the same time, it is itself subjected.

Not only should care be taken to select solid ground for buildings, or, if it becomes necessary to build on loose earth, to fortify the unstable foundation, but, in earthquake centres special attention should be given to the mode of construction. In this direction the Japanese have made most progress. In a country where over a thousand shocks occur each year, it is natural that means for relief from their most terrible effects should be carefully devised. From the Japanese, those who live in other earthquake centres may learn important lessons in the proper building of earthquake-resisting structures. It is little short of criminal carelessness to rebuild, after a devastating earthquake, apparently without giving a thought to the future.

It is entirely within reason to expect that careful study in any given locality would reveal the exact site and extent of fault lines, and determine the probable danger from destructive shocks over the area. Indeed, I consider it not at all improbable that such studies could be made to serve as the basis of accurate prediction of the coming of a severe earthquake in sufficient time to warn the inhabitants of its approach.

There is not a little evidence that there is a certain relation between the time of occurrence of earthquakes and other conditions not commonly recognized as having a bearing on earth movements. Future investigations will throw more light on this question, possibly eliminating some of the inferred relationships, and establishing others now suspected. It has been suggested that there is a relation between earthquakes and air pressure; and, with the frequent changes in weight of the air column, it is not impossible that there is some such relationship; but long-continued and careful studies are required to establish it, if, in fact, it exists. Another suggested relationship is that of the pull on the earth by the moon and sun, which varies in intensity from time to time and from place to place. Not enough facts are now at hand to either deny or affirm this suggested relationship. The same may be said with reference to magnetism.

These possible factors in earthquake cause, if they operate at all, in all probability act only to finally start the movement for which strains have been accumulating as a result of other causes. In connection with these more fundamental causes for earthquakes, there are also some possible relationships. There is known to be a slight movement of the pole, and there is already fairly clear evidence that this affects earthquake occurrence, though just to what extent is not yet clear. A change in the axis of rotation of a sphere flattened at the poles and bulging at the equator, though ever so slight, necessarily calls for readjustments in the earth; and, from these, earthquakes may well follow.

While it is generally denied by seismologists that there is reason to associate earthquakes with distant volcanic eruptions,—for example, the San Francisco earthquake and the eruption of Vesuvius at nearly the same time,—there is, nevertheless, reason for believing that earthquakes and movements of molten rock near at hand are, at times at least, sympathetically related. In the earthquake-stricken Calabrian region of south Italy, there has been a rather striking series of coincidences of severe earthquakes either preceding or following vigorous outbursts of the neighboring volcanoes of Vesuvius and *Ætna*; and, less strikingly, there have been coincidences between earthquakes and volcanic eruptions in the West Indies.

It has been one of my objects in this paper to point out that, while much progress has already been made in the study of the cause and effects of earthquakes, there are many unsolved problems. The solution of these is a matter of great scientific interest; but, aside from this, there is a possibility, and I think I may say even probability, that the solution of these problems will be a matter of the highest importance to the human race. The army of investigators scattered over the world are working upon them as best they can with scanty means and insufficient equipment. There is need of more workers, many more stations, better equipments and more intimate coordination of results. To provide the means for this, which any one of scores of Americans could easily do, would be a service of the highest importance not only to science, but to mankind in general. Few scientific investigations offer promise of greater results to science and higher benefits to humanity.

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